Effect of milling parameters on microhardness and microstructure during dry and flood milling of Ti-6Al-4V

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Abstract. The current study focuses on investigating the effect of milling parameters on the microhardness during dry and flood milling of Ti-6Al-4V. Dry and flood milling were performed while varying spindle speed (120, 150, and 180 rev/min), depth of cut (1, 1.5 and 2 mm), as the feed rate (4.6 mm/min) was kept constant. Subsequent to milling, milled surfaces microhardness were measured and microstructure evolution was analysed using an optical microscope. It was established that the deformation of beta phase increased with increase of spindle speed during dry milling while during flood milling there was no microstructural change associated to the increase of the spindle speed. On the other hand, the hardness increased as result of increase of spindle speed during both dry and flood milling. Flood milling generated a maximum hardness of 338.44 HV at 180 rev/min which is superior to maximum hardness of 336.36 HV produced during dry milling. Dry milling at 1.5 mm depth of cut generated maximum deformation of beta phase while during flood milling maximum deformation was recorded at 2 mm depth of cut. The hardness increased with increment of depth of cut during flood milling while it decreased with increase of depth of cut during dry milling.

1. Introduction

The use of titanium and its alloys in aerospace industries, chemical industry and biomedical industry has gain a huge amount of momentum owing to its outstanding strength to ratio, and excellent corrosion resistance [1]. However, even though titanium possess such outstanding attributes, it is regarded as hard to machine material due to its poor thermal conductivity, low modulus of elasticity and ability to undergo strain hardening [2]. According to on Singal et al. [3], milling is a machining process which is responsible for removing material with the use of multi edged cutting tools. During milling, parameters such as cutting speed, feed rate and depth of cut need to be properly selected since these parameters affect the surface integrity of the workpiece which consequently impact on the performance of the workpiece when is in-service [4]. Cutting fluids at higher cutting speeds perform a function of cooling and of lubrication at low cutting speed [5]. However, dry machining is preferred over machining with lubricants due to low production cost and environmental friendliness associated with dry machining even though dry machining is hazardous in terms of health of the operator due to dust generated during dry machining [6]. Sun and Guo [7] argued that the microhardness of the milled surface decreased with increase in cutting speed from 65 to 110 m/min using water soluble cutting flood, but deformation of beta phase on the subsurface microstructure increased with increase of cutting speed (80-110 m/min) while there was no deformation of beta phase at low cutting speed (50-65 m/min). This is in contrary with study conducted by Mousssaoui et al. [8] which focused on the investigation of milling on surface integrity of Ti-6Al-4V alloy on metallurgical characteristics (microstructure and microhardness). They established that increase of cutting speed from 54 m/min to 74 m/min resulted in an increase of milled surface hardness during dry milling but no alteration of microstructure below the machined surface was observed when the cutting speed and depth of cut were increased. On the other hand Sun et al. [9], investigated the effects of cutting parameters during dry machining of Ti-6Al-4V alloy using ultra hard tools. They reported that when the cutting speed was increased from 30 to 60 m/min during dry machining of Ti-6Al-4V, the machined surface experienced thermal softening phenomenon since the hardness decreased. Furthermore, Rotella et al [10] studied the effects of cooling method during machining of Ti-6Al-4V. They reported that the microhardness of the machined surface increased with

increase in cutting speed during dry, MQL and cryogenic machining. Safari et al. [13] argued that α grains of subsurface microstructure experienced deformation phenomenon, this phenomenon became more evident as the cutting speed increased. According to them the deformation of α grains was due to the concurrent effect of mechanical and thermal load.
In this paper the effect of spindle speed on the microstructure and microhardness during dry and flood milling is investigated. This will benefit industries predominantly in South Africa which specialize in the milling of Titanium alloys in terms of which spindle speed and cooling method (dry or flood) in order to produce a quality milled workpieces.

2. Experimental procedure

Titanium grade 5 alloy plates of 100 x 100 x 7 mm were milled using vertical milling machine (Pinnacle PK-GRSM-V2). Milling was conducted in dry and flood condition by varying spindle speed (120, 150, and 180 rev/min), while the feed rate was kept constant at 4.6 mm/min and depth of cut were 0.5, 1, 1.5 and 2 mm). Tungsten carbide cutting tool was used for the experiments and a new cutting tool was used for each milling parameter in order to eliminate the effect of tool wear. Subsequent to milling microhardness profile was conducted using micro Vickers hardness tester. A load of 300 g for 15 seconds was applied on the milled surface samples and the microhardness was measured along the feed direction. Metallographic sample preparation steps (Mounting, grinding, polishing and Etching in Kroll's reagent) were carried out for microstructure analysis using optical microscope. An Olympus BX51M optical microscope was used.

3. Results and discussions

The parent material's microstructure is depicted in **Fig. 1** and alpha phase (α) is represented by light area while beta phase (β) is represented by dark area.

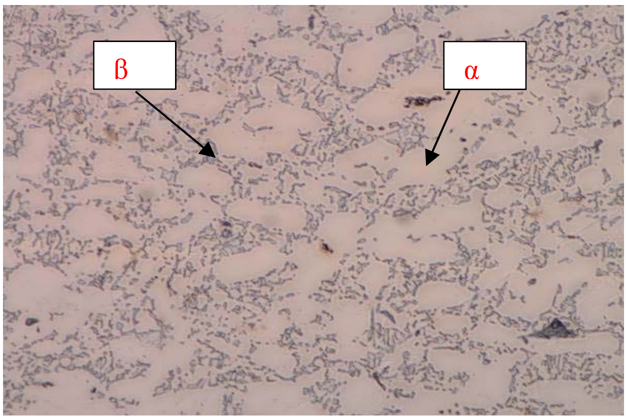


Figure 1.: Depicting microstructure of parent material

a. The effect of spindle speed

Fig. 2a, **2b** and **2c** show that the deformation of beta phase (beta phase became smaller) increased with increase of spindle speed and maximum deformation of beta phase was experienced at a maximum spindle speed of 180 rev/min. This is in line with the microhardness results as depicted in **Fig. 3** which shows that increase of spindle speed from 120 to 180 rev/min resulted in an increase of microhardness wherein a minimum, medium and maximum microhardness of 317.88 HV, 328.28 HV and 336.36 HV were generated at 120 rev/min, 150 rev/min, and 180 rev/min respectively.
According to Rotella et al [10] the increase of hardness with increase of spindle speed is due to strain hardening being superior to thermal softening.

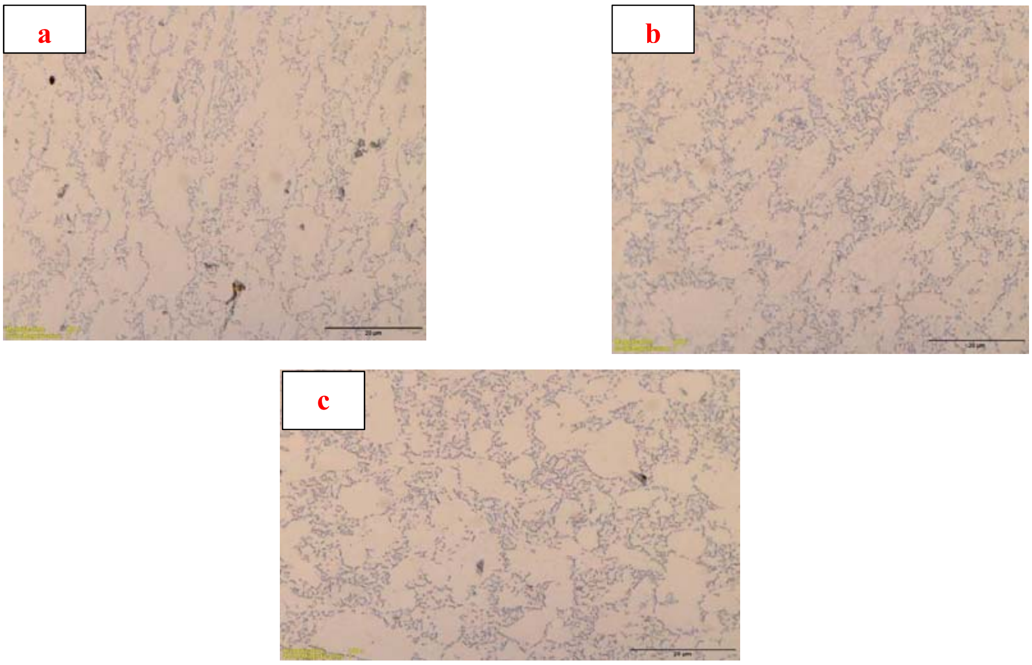


Figure 2: Dry milled surface microstructure at (a) 120 rev/min, (b) 150 rev/min, and (c) 180 rev/min

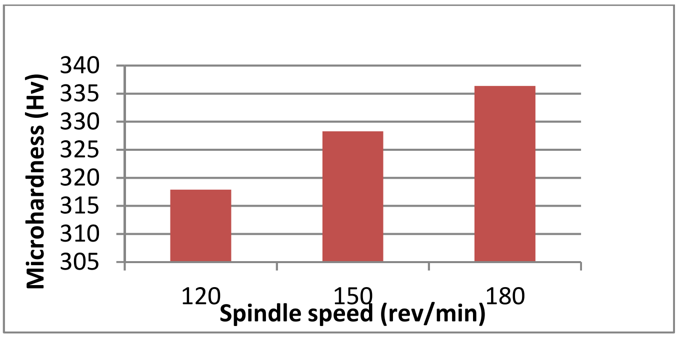
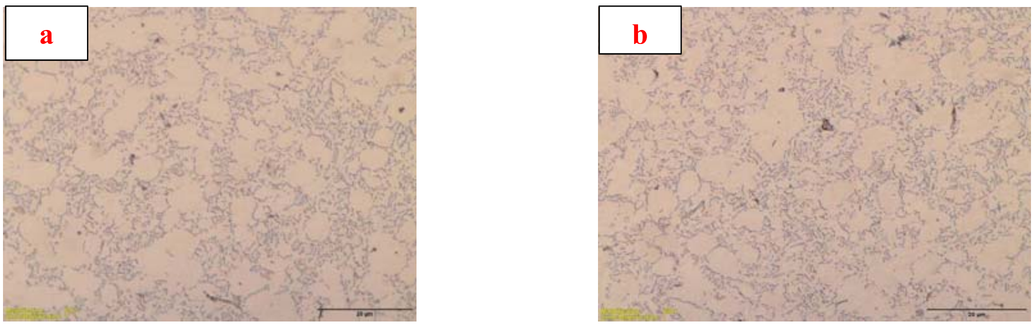


Figure 3: Microhardness vs spindle speed

During flood milling, the surface microstructures did not reveal any alteration with increase of spindle speed as shown if **Fig. 4a**, **4b** and **4c**. However, it was found that the milled surface microhardness increased with increment of spindle speed as it can be seen in **Fig. 5**. Furthermore, **Fig. 5** show that a minimum microhardness of 325.62 HV was generated at minimum spindle speed of 120 rev/min and a moderate microhardness of 331.1 HV was generated at medium spindle speed of 150 rev/min while a maximum microhardness of 338.62 HV was generated at maximum spindle speed of 180 rev/min. The same findings were established by Xiaoyong et al [12], which revealed that the subsurface microhardness decreased with increase of cutting speed for a depth of 100 µm while there was no alteration on the microstructure as a result of increase of cutting speed. The increasing hardness trend as a result of increase of spindle speed is due to strain hardening [11].



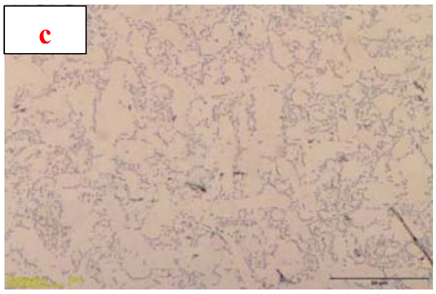


Figure 4: Flood milled surface microstructure at (a) 120 rev/min, 150 rev/min and (c)180 rev/min

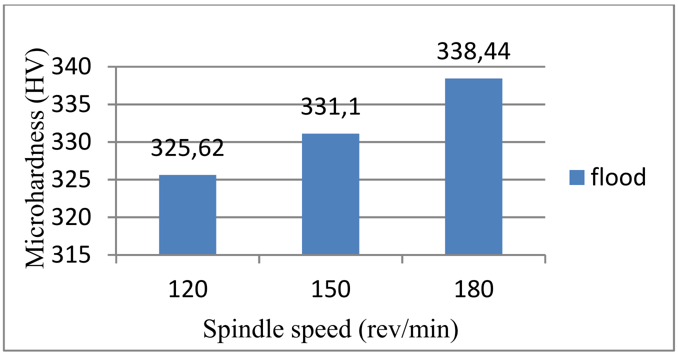


Figure 5: Microhardness vs spindle speed

b. The effect of depth of cut

During dry milling, it was found that the deformation of beta phase increased when depth of cut was increased. However, maximum deformation was experienced at moderate depth of cut (1.5 mm) and minimum depth of cut was experienced at minimum depth of cut (1 mm) as it can be seen in **Fig. 6**. Furthermore, it was established that during dry milling that the hardness decreased with a decrease of depth of cut wherein a minimum of 328.74 HV was generated at maximum depth of cut of 2 mm. A maximum hardness of 338.7 HV was recorded at minimum depth of cut (1 mm), this is shown in **Figure 7.** The decrement of hardness is due to thermal softening [13].

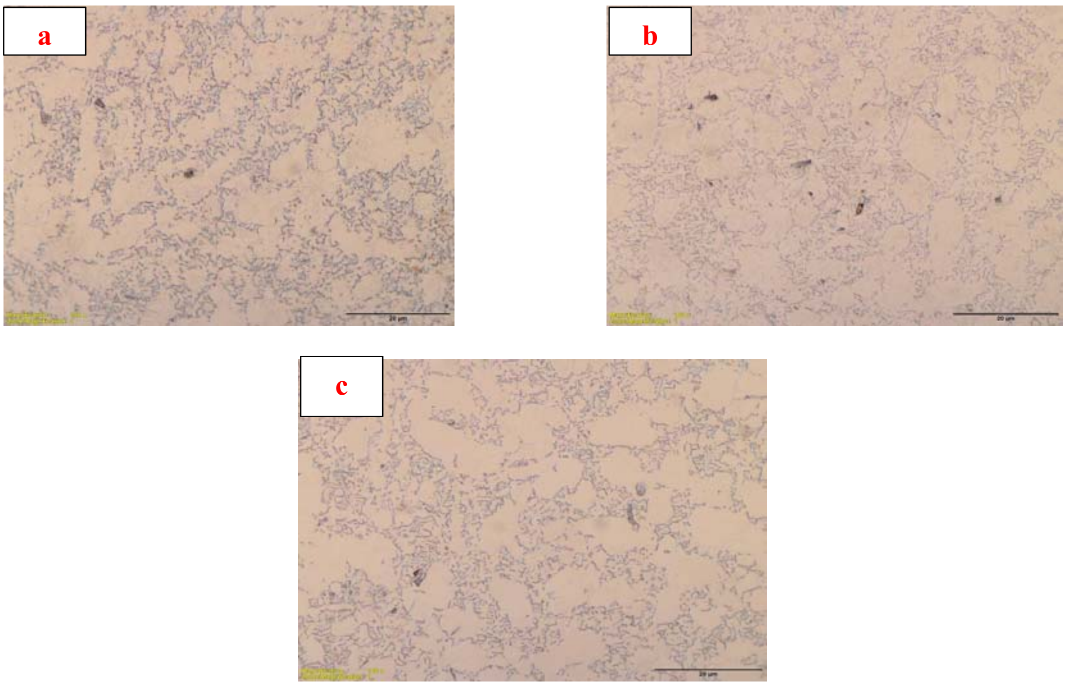


Figure 6: Dry milled surface microstructure at (a) 1 mm, (b) 1.5 mm, and (c) 2 mm

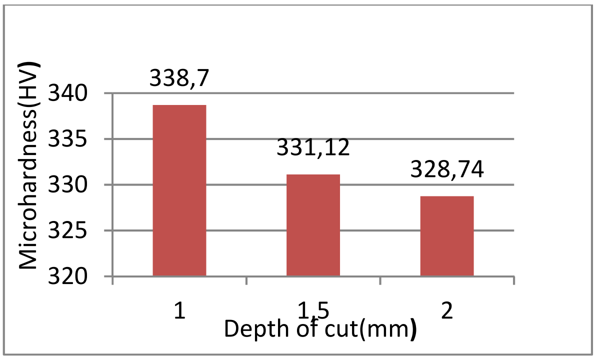


Figure 7: The effect of depth of cut on the microhardness for samples produced in the dry condition

Fig. 8 shows that during flood maximum deformation of beta phase was experienced at moderate depth of cut (2 mm) while minimum deformation was experienced at 1 mm depth of cut. This is supported by **Fig. 9** which shows that during flood milling, the hardness increased with increment of depth of cut wherein a minimum hardness of 314.97 HV was recorded at minimum depth of cut (1 mm) and a maximum hardness of 326,84 was recorded at maximum depth of cut (2 mm).

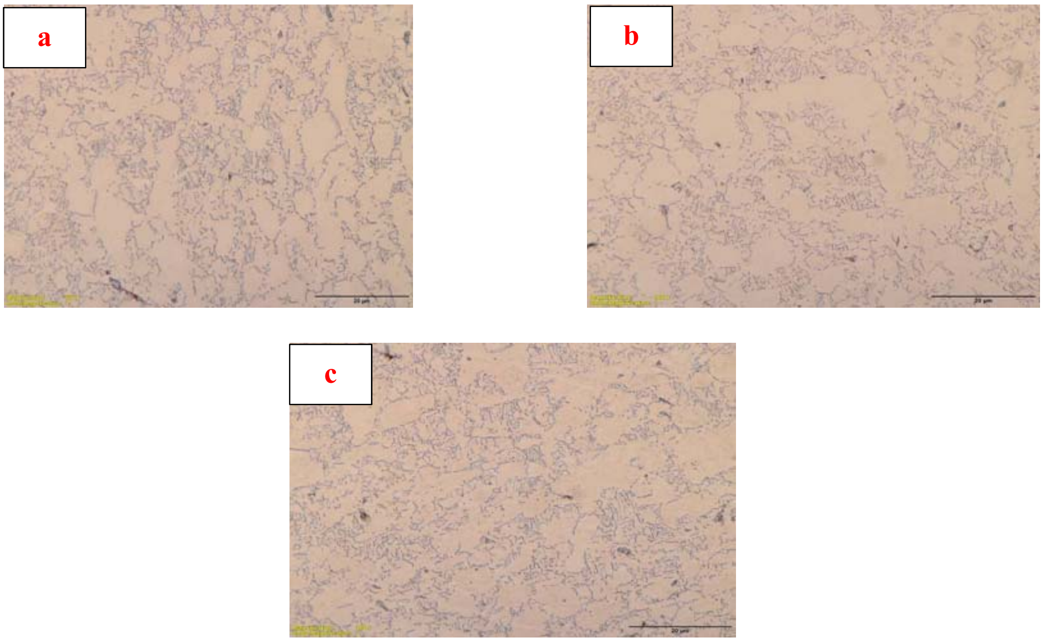


Figure 8: Flood milled surface microstructure at (a) 1 mm, (b) 1.5 mm, and (c) 2 mm

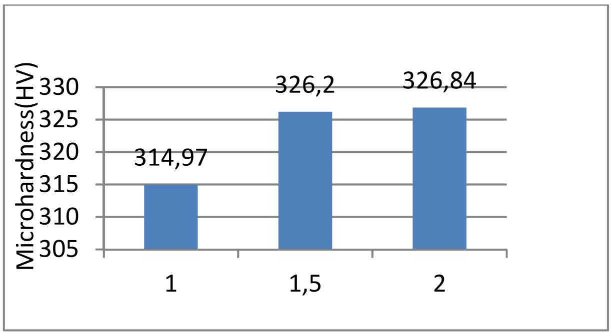


Figure 9: The effect of depth of cut on the microhardness for samples produced in the flood condition

4. Conclusions

The current study established that increase of spindle speed during dry milling resulted in increase of deformation of beta phase while increase of spindle speed during flood milling did not alter the microstructure. Moreover, increase of spindle speed during both dry milling and flood milling resulted in an increase of hardness. Minimum and maximum hardness were generated at 120 and 180 rev/min during both dry and flood milling. Furthermore, it was found that the highest hardness (338.44 HV) was generated during flood milling. Furthermore, based on the current study's findings, it is advisable to use flood milling over dry milling since dry milling produced a maximum (336.36 HV) hardness which is lower than a maximum hardness during flood milling. On the other hand it was found that during dry milling, medium depth of cut (1.5 mm) generated maximum deformation of beta phase while during flood milling maximum deformation of beta phase was experienced at 2 mm depth of cut. Moreover, the hardness decreased with increment of depth of cut during dry milling while during flood milling it increased.

Acknowledgement

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